

An Archive of Spectra from the Mayall Fourier Transform Spectrometer at Kitt Peak

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ABSTRACT

We describe the SpArc science gateway for spectral data obtained during the period from 1975 through 1995 at the Kitt Peak National Observatory using the Fourier Transform Spectrometer (FTS) in operation at the Mayall 4-m telescope. SpArc is hosted by Indiana University Bloomington and is available for public access. The archive includes nearly 10,000 individual spectra of more than 800 different astronomical sources including stars, nebulae, galaxies, and Solar System objects. We briefly describe the FTS instrument itself, and summarize the conversion of the original interferograms into spectral data and the process for recovering the data into FITS files. The architecture of the archive is discussed, and the process for retrieving data from the archive is introduced. Sample use cases showing typical FTS spectra are presented.

Subject headings: miscellaneous — catalogs — surveys

1. Introduction

During the period from the mid-70s through the mid-90s, the Kitt Peak National Observatory operated a Fourier Transform Spectrometer (FTS) on the Mayall 4-m telescope. The FTS produced spectra primarily in the wavelength regime 1 to 5 μm (10,000 to 2000 cm^{-1}), mostly at relatively high spectral resolution. During this period, before the development of infrared arrays, an FTS permitted efficient observation of infrared spectra. Nearly 10,000 sources were observed with the 4-m FTS, many of them multiple times. Targets included a variety of normal and peculiar red giants, solar type stars, M dwarfs, and variable stars, as well as nebulae and galaxies. Early type stars were occasionally observed to permit the removal of telluric absorption lines. Observations at high spectral resolution were limited to a magnitude of $K=4$ or brighter, although some fainter targets were observed at lower resolution.

Fourier transform spectroscopy has a number of advantages over dispersive (grating) spectroscopy. It is inherently a broad spectral band technique. The spectra in the 4 meter FTS archive generally cover an atmospheric window in the J, H, K region and at least a 5% (100 cm^{-1}) bandpass in the thermal L and M windows. The throughput is high and there is no scattered light. The instrumental function is well defined and the response is photometric. The wavelength scale is well defined without need for reference to a dispersion relation and shifted by a small, constant amount from absolute. The spectral resolution is fully adjustable. FTS instruments are typically highly stable with time. A dual input design is readily implemented allowing first order removal of background, scintillation, etc. In summary the photometric accuracy and frequency calibration of the spectra are limited by photon noise rather than instrumental characteristics. For these reasons this technique is very popular in laboratory spectroscopy. A wider view of the technique and applications can be found in Davis et al. (2001). However, the non-dispersive nature of the technique is also a limitation. With the advent of infrared array detectors, Fourier transform spectroscopy was at an increasing sensitivity disadvantage. Multiplexing disadvantage in spectrometers of high sensitivity is discussed by Ridgway & Hinkle (1988).

For bright objects we believe the spectra obtained with the 4-m FTS are unsurpassed. The collection of 4-m FTS spectra forms a unique dataset that will not be duplicated with modern instrumentation. More than 120 refereed papers using FTS data have been published since 1978, including nearly 25 refereed papers since 2000¹. The most highly cited works are seminal studies of CNO and their isotopes in red giants by Smith & Lambert (1985, 1986, 1990) and Lambert et al. (1986), as well as studies of circumstellar material and mass flows

¹A list of refereed papers utilizing FTS data is available at <https://sparc.sca.iu.edu/index/papers>.

in both young stellar objects and red giants with high mass loss rates (Hinkle et al. 1982). Saar and Linsky’s 1985 paper on magnetic fields in the dM3.5e star AD Leonis conclusively demonstrated the presence of photospheric magnetic fields in dMe stars, and Jorissen et al. (1992) used FTS spectra for the first measurements of the fluorine abundance in stars other than the Sun. Mayall FTS data continue to be useful for a broad range of astrophysical questions, even 20 years after the FTS was formally retired from service. Recent papers include studies of dynamic model atmospheres and outflows, star forming regions, and stellar abundances. Smith et al. (2013) used FTS spectra to provide a fundamental calibration of the APOGEE line list. The excellent photometric quality of the spectra and high wavelength precision are ideal for atlases (Hinkle et al. 1995; Wallace & Hinkle 1996; Wallace & Hinkle 1997; Meyer et al. 1998; Wallace et al. 2000).

Here we describe the publicly available archive of spectra from the 4-m Mayall FTS. In Section 2 we summarize the characteristics of the instrument itself. Section 3 is devoted to a discussion of the data reductions and characteristics of the spectra. In section 4 we discuss the structure and features of the archive, and in Section 5 we describe the contents of the archive and suggest use cases. In Section 6 we summarize our work.

2. The Mayall Fourier Transform Spectrometer

In the mid-1970s a prototype FTS with 10 cm travel and a design based on a modified commercial instrument was installed at the f/160 coudé focus of the Mayall 4 m telescope on Kitt Peak. The 4 m telescope had been dedicated in 1973 and this was the first scientific use of the coudé focus. The prototype FTS was part of a collaboration between D. Hall and S. Ridgway based on technology developed by J. Brault for solar and laboratory spectroscopy. The intent was to provide a new capability for near-infrared spectroscopy of planetary and galactic sources at the new telescope facility. In 1978 September the prototype FTS was replaced with a facility instrument (Hall et al. 1979). The facility Mayall FTS was significantly more versatile and efficient than the prototype. The maximum travel, which defines the resolution, was 1.4 m. The design permitted moderate to very high resolution² ($\sim 20 \text{ cm}^{-1}$ to 0.005 cm^{-1}) observations from the red-optical through the mid-infrared ($\sim 15000 \text{ cm}^{-1}$ to 700 cm^{-1}). This facility FTS fully utilized in an astronomical application the by then mature technology of Fourier spectroscopy. A review of the FTS technique with

²Throughout this paper we will use wavenumbers in cm^{-1} units. These are the natural units in Fourier spectroscopy. The spectra are transforms of intensity measurements. The intensity is measured as a function of the path difference which is typically measured in cm. Hence the spectrum and resolution is in inverse cm.

emphasis on the application at Kitt Peak³ can be found in Brault (1985). References to astronomical applications of Fourier transform spectroscopy are given in Hall et al. (1979).

2.1. General Description

Both of the 4 m FTS instruments were fed by the f/160 coudé beam. A key feature of the telescope, and in the use of the FTS, was the rapidity with which the 4-m could be reconfigured between f/8, f/16, and f/160. This was done by moving the telescope far to west and rotating sections of the top end to change the secondary mirror, and took no more than 10 minutes. Focal conversion was especially advantageous to coudé use since time could be shared between Cassegrain and coudé instruments. The FTSs had a dual beam design (star plus sky in one beam and sky in the other) that allowed for sky cancellation. This enabled near- and mid-infrared spectroscopy during daylight hours in clear sky conditions. The FTS employed a rapid scan design with an interferogram recorded in a few minutes. Cancellation of sky was achieved by taking and co-adding scans using an abba sequence. As use of the facility FTS matured, a large fraction of the observations took place during daylight morning hours following nighttime use of an f/8 instrument.

Both the prototype and the facility FTSs were bench-mounted coudé instruments directly fed by the coudé beam. A photograph of the facility FTS in the Mayall’s east coudé room is shown in Figure 1. A schematic of the optical layout of the facility FTS, copied with permission from the instrument description presented by Hall et al. (1979), is shown in Figure 2. The optical package was held on a large optical table mounted on air supports. The individual optics were held by two axis adjustable Burleigh mounts. The east coudé room is a closed room with a small window providing a beam path from fifth mirror in the coudé train to the FTS. The coudé number five mirror was servo-driven to track the beam from the moving telescope onto the center of the FTS mirror 1 (Figure 2). Mirror 1, an f/65 spherical mirror, reimaged the telescope beam onto dual entrance apertures (at mirror 4 in Figure 2) and placed the pupil of the entrance apertures at infinity. The entrance apertures were drilled into a spherical mirror and were either 3.5 arcseconds diameter for non-thermal or 2.7 arcseconds diameter for thermal IR observations. Note that at the time the FTS was used the typical full width of the coude images was 3 arcseconds. The apertures were typically separated by 50 arc seconds. These beams, source plus sky in one beam and sky in the other beam, passed through the FTS in opposite directions (APT1 and APT2 in Figure

³During the lifetime of the Mayall FTS, another FTS operated at the McMath-Pierce solar telescope. The McMath FTS was optimized for precision measurements of laboratory and solar sources.

2), which resulted in first order sky cancellation. Light reflected from mirror 4 was directed to a TV for guiding.

The light that passed through the apertures was collimated by mirror 5 on the A side and an identical mirror on the B side and recombined at the top half of a beamsplitter (6). In Figure 2 the arrows show the number of recombined beams. The beamsplitter was a thick plate of an optical material selected for the wavelength of the observation with 50/50 reflection/transmission coatings on opposite sides of the top and bottom and anti-reflection coatings opposite to the coatings (Figure 3). From the beamsplitter the light traveled to two identical cat’s eye assemblies (7-8-9-10-11 in Figure 2). The cat’s eyes utilized a quartz front plate with a convex reflection spot (9) between entrance apertures (7, 11) and quartz concave primaries (8, 10). At zero path difference the centers of curvature of both the concave and convex surfaces were on the beamsplitter. The result is that the input aperture was imaged on the cat’s eye secondary and the pupil re-imaged on the lower half of the beamsplitter. This innovative cat’s eye design is discussed further by Hall et al. (1979). The cat’s eyes did not move symmetrically about zero path. The B side cat’s eye was on rails and accounted for the major travel. The cat’s eye on the A side was on a hinge mount and moved rapidly to account for path errors. The beams recombined at 12. From there the beam went to camera mirrors (13 and the corresponding mirror on the B side). The final reflections were flats that sent the light into dewars (14 on the A side and another on the B side) containing single element detectors. The overall number of reflections involved was five in the telescope and eleven plus two beamsplitter passes in the interferometer. The FTS reflective surfaces were silver with a ThF₄ overcoating. The throughput at K was about 20 percent (including the atmosphere). The modulation efficiency at K was typically near 80 percent.

2.2. Features Impacting the Spectra

2.2.1. Beamsplitters and Detectors

The facility FTS optical design allowed operation from 0.3 to 30 μm by using interchangeable beamsplitters and detectors. This was facilitated by making the beamsplitter a plain-parallel plate (Figure 3). The design permitted beamsplitter changes with only minor re-alignment of the FTS. Beamsplitter changes could and were carried out during an observing session. The beamsplitters were kinematically mounted and the realignment procedure (Simmons 1978) could be carried out in less than 30 minutes. By contrast the McMath FTS beamsplitters were wedged and changed infrequently on a scheduled basis. The cost of the plane-parallel beamsplitter design is that multiple internal reflections result in channel spectra. The beamsplitter thickness and antireflection coatings reduced the channel spectra.

However, with certain configurations the channel spectra are prominent enough to be seen in the interferograms. The fringing was sometimes mitigated by removing the signal at the channel frequency from the interferogram during data reduction. Zeroing the interferogram introduces some ringing. Fringes from beamsplitter channel spectra have a spacing of several per wavenumber.

For observations from 1.0 to 5 μm , two CaF_2 beamsplitters were used depending on wavelength. The detectors were InSb single channel detectors operated in photovoltaic mode. For longer wavelength observations a NaCl beamsplitter was available and at shorter wavelengths a fused silica beamsplitter was used. These were largely used for program with visitor supplied detectors.

Three sets of InSb detectors were available and optimized for different signal levels. Dewars A and B had LN2 cooled InSb detectors with 1 mm diameters that were intended for broad band, bright sources or thermal IR observations. Dewars C and D were LHe cooled InSb detectors of the smallest diameter available and tuned for faint objects. A third set of dewars, E and F, used 0.5 diameter InSb detectors. These were typically used at LHe temperature. While the normal mode of operation used a pair of detectors, it was possible to operate with a single detector but with the loss of half of the signal. The detectors were always used in combination with a cold blocking filter. Changing the blocking filter required opening the dewar. Some near-IR band passes required a cold long wave filter and a warm short wave filter. The most common example is the H-K filter which was a cold thick green glass filter to block thermal IR combined with a warm 1.6 micron long pass filter. Some filters had fringing. This will appear with periods greater than a wavenumber.

Dichroic mirrors that could be used in place of the bending flats (labelled 14 on the optical diagram) allowed, for instance, K and H band spectra to be observed simultaneously with the low noise detectors rather than with a single broad band filter and noisier detectors. When the dichroic was used the interferograms from both sets of dewars were combined. These spectra should not be confused with broadband spectra in the archive. Other dichroic combinations were possible, for instance M band or L band and K.

N_2O cells were also available that could be placed either behind the input apertures or in front of the dewar windows. These cells added lines to the K band spectrum as a velocity reference.

The signals from matched detectors at the two outputs were both summed and differenced. The sum removed the interferogram to leave the instantaneous stellar flux. This was displayed to provide guiding and transparency information. The differenced signal yielded an interferogram with negligible DC offset. The difference signal, electrically filtered to the

appropriate bandpass (see scan control and scan parameters below), was ratioed to the electrically filtered sum signal to eliminate amplitude modulation of the interferogram due to guiding errors, seeing, etc.

2.2.2. *Scan Control*

The 4 m FTSs were rapid scan devices that moved the carriage continuously during an observation. Data was recorded with the carriage moving both away from (forward) and toward (reverse) the beamsplitter. During the course of an observation the forward and reverse scans were combined separately. Hence, each observation consists of two spectra. Occasionally an instrumental problem would occur that destroyed one or the other of the averaged scans so the archives do have some single spectra.

A Zeeman frequency stabilized 633 nm ($15798.003 \text{ cm}^{-1}$ in vacuum) helium-neon laser was used as the path difference reference. The laser was mounted behind FTS mirrors 5 and 13 with the beams propagating through tabs coated on the beamsplitter for 633 nm (Figure 3). It was found that the detectors could see scattered non-laser radiation when observing faint objects so a notch filter was installed before the laser light entered the FTS. The reference laser chopped between Zeeman components at a rate F_z set by an internal oscillator. For the 4 m FTS $F_z=1.800000 \text{ MHz}$. The two Zeeman laser components had different polarizations. Polaroid filters on each side of the beamsplitter separated the components. They were optically remixed and detected by a silicon diode. The phase shifts of the signal relative to the oscillator monitored the path difference. Continuous phase-lock techniques were used to achieve path difference position and velocity control. For $15798.003 \text{ cm}^{-1}$ a fringe is $0.633 \mu\text{m} = 6.33 \times 10^{-5} \text{ cm}$. The path difference was held within an RMS error of 2 milli-fringe RMS error during constant velocity translation, i.e. the path difference was held to 1 nm and the position of the moving cat's eye to half this, 0.5 nm. The control system was common with the McMath solar/laboratory FTS and a detailed description is given by McCurnin (1981).

2.2.3. *Scan Parameters – M,K,S*

The carriage of the FTS scanned at a set constant rate. The user interface of the control system used three integer parameters to control the carriage velocity, sample rate, and range of travel of the carriage, M, K, and S. These three parameters appear in the headers and along with F_z and σ_{laser} were fundamental to taking and reducing the data. By definition

the speed of the moving carriage in laser fringes per second was F_z/M and the sample rate in samples per second was F_z/K .

Three relations of interest can be derived from the definitions. If we define f as the data frequency in hertz, then it follows that

$$\frac{F_z}{M} = \frac{f\sigma_{laser}}{\sigma_{obs}} \quad (1)$$

where σ_{obs} is the wavenumber of the the observed data. From the previous section, $\sigma_{laser}=15798.003 \text{ cm}^{-1}$ and $F_z=1.800000 \text{ MHz}$, so

$$M = \frac{114\sigma_{obs}}{f} \quad (2)$$

The analog interferogram resulting from scanning the moving catseye was electrically filtered to remove out of band noise. Typically one of two filters was used. For bright or thermal IR objects the smallest wavenumber part of the spectrum was placed at 400 Hz. For fainter objects the frequency response of the detectors was better matched by scanning five times slower with the low cut off at 80 Hz. Following these rules M was calculated for the wavelength region to be observed. Values associated with some common settings, for instance the K band are 1140 for 400 Hz. The analogue electrical filters and the other control electronics were rack mounted in the observing room next to the FTS room (Figure 4)

M/K is the number of samples per laser fringe. This must be larger than 0.5 to prevent under sampling the interferogram. Thus the high frequency edge of the electrical filters were 1000 Hz and 200 Hz. The largest wavenumber that can be observed unaliased is given by $\sigma_{laser}M/2K$. This of course had to be larger than the blue edge of the optical filter. Common settings for K and M were 900 and 1140. $K=900$ produced a 2 KHz sample rate. $M = 1140$ placed the alias at 10005 cm^{-1} .

There are a few observations that cover the entire J-H-K region. A more common configuration was H-K or a single atmospheric window. Since an FTS is not dispersive the noise from the single element detector is distributed across the entire band pass Ridgway & Hinkle (1988). In the thermal IR the background noise requires narrow filters. At M the filters were typically 100 cm^{-1} broad.

A third scanning parameter sets the length of the scan. The total number of samples recorded was MS . The total distance traveled in units of reference laser fringes was KS . The time to obtain a scan is the distance traveled divided by the velocity, i.e. KSM/F_z .

2.2.4. *Position of the Central Fringe*

The interferogram is a map of the interference with path difference. This must be measured from zero path difference which is the middle of the 'central fringe.' The central fringe contains the lowest frequency information regarding the overall shape of the spectral bandpass, continuum, and zero point. In practice the central fringe was found in the data during the reduction. The central fringe was used to interpolate the interferogram so the output of the Fourier transform was in one plane of conjugate space. This required data on either side of the central fringe. Interferograms can be taken with the central fringe in the middle or at one end. The 'in the middle' variety is called two sided and had the advantage that all the data were converted into the spectral domain. The central fringe near one end was called one sided. Typically approximately ten percent of extra interferogram was scanned before the central fringe. While the ten percent was lost time, the advantage was that the total scan time for the interferogram was cut approximately in half. This allowed more scans to cancel background. The sidedness of the interferogram is recorded in the headers. The total path difference gives the resolution so knowledge of the sidedness and K and S is required to compute the resolution.

2.2.5. *Resolution versus Point Spacing*

A path difference of 1 cm results in a theoretical resolution of 1.0 cm^{-1} . To obtain a path difference of 1 cm, the carriage must move 0.5 cm since the light travels out and back from the beamsplitter. So 1 cm^{-1} of theoretical resolution is a travel of $0.5 \text{ cm} / 6.33 \times 10^{-5} \text{ cm} = 7899$ fringes. The path difference is just one of several criteria that can be used to define spectral resolution (Davis et al. 2001). A definition of resolution of more practical use is the path difference that produces an instrumental profile with the resolution as the full width at half maximum. This is 9532 fringes for 1 cm^{-1} . Since the FTS instrumental profile results from the transform of a rectangular function, i.e. the interferogram, the natural instrumental profile is a sinc function. The ringing side lobes of a sinc function can be damped by apodizing, i.e. convolving the spectrum with a damping profile, or alternatively multiplying the interferogram with a weighting function. A useful discussion and suggested apodizing functions can be found in Norton & Beer (1976). Function 2 of Norton & Beer requires a path difference of 13345 fringes to produce a FWHM of 1 cm^{-1} . All the 4 m FTS archive data are unapodized. For stellar spectra the sinc function profile will not be obvious. However, we recommend apodizing the data from the facility FTS. For most applications a Gaussian is acceptable. Convolution with an apodizing function of appropriate FWHM should also be used to lower the spectral resolution if this is desired (see for example Wallace

& Hinkle 1997).

Interferograms were converted to spectra using the Fast Fourier Transform (FFT) algorithm. This requires a data set of length a power of two. In the reduction process zeros were added to the end of the interferogram before it was transformed. The effect of adding zeros is to interpolate the spectrum. *As a result, the point spacing of the spectra is not simply related to the resolution.* The resolution must be computed by dividing the KS product into the number of fringes for 1 cm^{-1} for the line profile you are using. For instance for unapodized data and using the FWHM definition, the resolution is $2*9532/\text{KS}$ for two sided interferograms. The resolution will always be slightly lower than the point spacing.

From the M, K, and S values it is possible to compute the point spacing as well as the resolution. The recipe is first to compute the number of points, MS, but remember to divide by two if the interferogram is two sided. Then find the next power of two larger than this number. Take the power of two number of points and divide it into the wavenumber of the alias, $\sigma_{\text{laser}}M/2K$, by the power of two number of points. This can be useful in understanding the oldest archival data where header information is missing.

The prototype FTS had an instrumental FWHM $\sim 10\%$ greater than the theoretical value. This resulted from instrumental apodization associated with the vignetting of the pupil on the beamsplitter with path difference. The facility FTS yielded theoretical sinc instrumental profiles. The instrumental profile as indicated by sharp terrestrial lines remained stable over the life of both the prototype and facility instruments. The cat’s eyes were never disassembled. While the collimators were recoated the instrument never underwent a major disassembly during its lifetime.

2.2.6. Wavelength Scale Complications

As discussed above the frequencies of all points in a spectrum are expressed as multiples of the reference laser frequency. The 4 m FTS was not in vacuum enclosure so a compensation for the dispersion of air was applied. Furthermore, the reference laser and source beam did not travel the same path through the FTS. As a result the step size for the reference beam is slightly different from that of the source beam. The shift in the wavenumber scale is small, typically a fraction of a km s^{-1} . This shift can be determined by measuring the velocities of the telluric lines. In some spectra reference N_2O lines are also present. Precision laboratory values for frequencies of lines in telluric and N_2O spectra can be found in the HITRAN database (Rothman et al. 2013; <https://www.cfa.harvard.edu/hitran/>).

2.3. The Demise of the FTS

The magnitude limit for the 4 m FTS in the K band was about $K=4$ for resolving power $R = \sim 20,000$ with S/N 100 in 4 hours of observing. The 4 m FTS was, in principal, able to observe all the sources found by the two micron IRC survey (Neugebauer & Leighton 1969), one of the system specifications. The low resolution K band limit was about $K=9$ at resolving power $R=\sim 1000$. Broad band (K+H) observations at $R = 70000$ and $S/N=100$ took about 4 hours at $K=+1$. The brightest stellar sources at K have magnitudes near -4 so the FTS could observe an impressive number of sources. While far more efficient than the previous generation of IR scanners, the FTS nevertheless fell short of the sensitivity expected by optical spectroscopists using photographic, let alone CCD, techniques.

The development of infrared array technology resulted in efficient dispersive spectrographs for the infrared that are orders of magnitude faster than the FTS (Ridgway & Hinkle 1988). Sensitivity is of critical importance to modern astronomical instrumentation and the FTS became obsolete. As usage declined, there were other pressures. The manufacturer of the A/D converter was no longer in business, and replacement parts were not available. Internal budget pressures at NOAO resulted in no allocation of funds to keep the instrument running. Continuing changes in the 4 m telescope control system were carried out without consideration of the effect on the aging FTS software. The final blow was the demand from engineering that the coudé optics path be used for cooling air for the telescope primary. The Mayall FTS was turned off in June 1995. Users of the archive data from the last two years should be aware that stuck A/D bits were common and there was no abba nodding.

3. FTS Spectral Data

3.1. FTS Data Reductions

Software (GRAMMY) to transform interferograms from the 4 m and solar FTSs was written in the 1970s for the Kitt Peak CDC 6400 computer. GRAMMY was a command driven package with a language of about 30 commands. GRAMMY was ported to DEC computers after the CDC computer was decommissioned but never rewritten. Due to the limited memory available at the time the software was written, revising the code, while conceptually fairly simple, was a complex undertaking. The transform sizes were typically 2^{18} to 2^{20} data points.

Very limited real time reduction was available at the telescope. Typically the only display available to the observer was of the interferogram, although the S/N ratio could be

approximated by using the noise levels on the DC photometric signal. Due to data storage limitations only the two (one for forward scans and a second for reverse scans) average interferograms were recorded for each observation.

As noted above the forward and reverse scans were transformed separately. Comparing these pairs of spectra is a valuable guide to the data quality. In principal the data should differ only by white noise. Some common problems can be seen in the difference, however. Deviations from zero may indicate clouds during the observation or distortion in the central fringe due to saturation. 60 cycle noise appears as evenly spaced bursts of noise. The relation of the noise bursts to their separation in wavenumbers can be computed using the M and K parameters. Guelachvili (1981) provides a detailed discussion of distortions in FTS spectra.

After the interferograms were transformed, the spectra were trimmed to remove regions outside of the filter band pass. These wavelength limits were input by the person reducing the data, are not constant for the same blocking filter, and as a result sometimes spectral information was lost. The software also transformed 4096 points around the central fringe to produce a low resolution spectrum. The low resolution transform was archived with the full resolution transform. The limited computer resources available at the time resulted in all the transforms being done on the main frame computer in Tucson. Thus it was possible to collect all the spectra into an archive. The archive was copied and combined multiple times. Fortunately from the beginning multiple copies of the archive were made and in spite of the poor quality of the recording media it was ultimately possible to recover all the spectra ever transformed. The full set of data occupied 63 9-track magnetic tapes.

Due to memory limitations the spectra were broken into 4096 point blocks each containing the full header information. Since the total length of the transformed spectrum is always a power of two, breaking the data into $4096 \text{ point} = 2^{12} \text{ point blocks}$ was convenient. Complex data were saved occasionally when the interpolation ('phasing') of the interferogram was uncertain. Changing the header information was difficult and required editing the spectrum with REDUCER=DECOMP, a program written by J. Brault for spectral analysis; header changes were rarely made.

With the advent of personal computers, the 9-track tapes were stored in memory. The FTS data storage format was a pre-FITS format invented by J. Brault. This format was readable on CDC and SUN computers but not easily decoded on other machines. To read the archived data on desktop computers, the archive was converted to ASCII using DECOMP on Sun computers before those, too, were retired. While standard DECOMP routines that had been in use for years were used to convert the archive to ASCII a small digitization error is noticeable if the wavenumber spacing is compared to the wavenumber of the start of each block.

3.2. Conversion to FITS Files

The 63 ascii "card image" files holding the full collection of FTS spectra are formatted into sequential records of information blocks and data blocks. Each of the files contains multiple observations. Generally, each observation includes a low resolution thumbnail and forward and backward scans at high spectral resolution; for some spectra, the complex output of the transform was also retained. Each forward and backward scan in the ascii file is broken into sub-scans of 4096 data points. Each observation begins with a big information block (BIB) with metadata associated with the observation, and each sub-scan within the observation begins with a small information block (SIB) that includes wavelength information and scaling information pertinent to that sub-scan.

The process to convert data in an ascii file to FITS format began with reading each record in the file and storing the metadata and data values. Since the observations were accumulated over twenty years, the output of the original processing was not always consistent. Each observation was checked by the software for inconsistencies and examined in detail if inconsistencies were found. As the file was read, subsequent scans that were determined to be the forward and reverse scans of the same FTS observation were matched. Subsequent records were determined to be associated if they have the same target, scan number, and data type. Subsequent records were determined to be forward/reverse pairs if they have the same target and have consecutive scan numbers. The first scan in a pair is identified as the forward scan. Generally, when only one scan is present, it is identified as a forward scan or backward scan depending on whether its scan number is odd or even. In some cases, the metadata were ambiguous as to whether records were from the same scan, or were a forward/reverse pair of the same scan. In such cases, the records were placed in different scans. In some early observations, scan numbers were not available in either the big or small information blocks. In these cases, the first scan was assigned as the forward scan and the second scan as the backward scan. A history string in each FITS header specifies from which input file and which records the data in that file come, as well as any inconsistencies identified.

The spectral data, stored as ascii integers, were converted to floating point using the scale factor and offset packing values associated with each sub-scan. The sub-scans associated with a scan were concatenated to produce a single spectrum for each image extension in the resulting FITS file, with the scan number as the FITS extension. In most observations, the forward scan was stored in FITS extension 1 and the backward scan as FITS extension 2.

3.3. Metadata

Most observations are accompanied by complete metadata. The original metadata available with FTS observations included observer-entered parameters (e.g. the astronomical target) as well as information from the instrument and telescope computers. We have, to the extent possible, preserved all metadata associated with each observation. For some observations, communication between the telescope and instrument was not operating normally, so for those observations, no telescope information is available. The KPNO or NOAO program number is also included, when available.

Telescope metadata included current epoch coordinates, UT and integer Julian dates, and the beginning and ending time of observation (in seconds) for most observations obtained starting in November, 1976 (prior to that date, telescope communication was not available) and ending in 1993. Starting in January, 1994, through 1995, telescope coordinates are not available for many of the observations. The starting and stopping sidereal time (in seconds), hour angle (in seconds), zenith distance (in radians), and air mass were also recorded. These data were converted to standard notation and recorded using appropriate FITS keywords.

Telescope coordinates were precessed to J2000 and matched with SIMBAD sources to confirm target identification and to obtain accurate J2000 coordinates to add to the FITS headers. This target confirmation is not possible for cases where telescope coordinates were not recorded. In nearly all cases the observer-entered target name was confirmed. In a few cases, the telescope coordinates did not match the observer-entered target name. These spectra are identified in Table 1. Users should examine these spectra carefully to assure they are the correct object. The exact pointing of many of the non-stellar objects is also uncertain, as are the specific identifications entered by observers, especially where the observer’s identification is cryptic and telescope coordinates are unavailable.

Instrument parameters included the number of co-added scans; detector, beamsplitter, and filter identifications; scan direction; detector gains, the point number of the central fringe, the laser and Zeeman frequencies; the high and low frequency cuts for the interferograms, the point number of the central fringe, and the FTS M, K, and S parameters.

Data reduction parameters include the final dispersion parameters, the spectral resolution, and the data units (all spectra are recorded and stored in vacuum wavenumbers).

Environmental metadata are also included when available, including the atmospheric pressure, temperature, and water vapor pressure. Wavenumbers are in vacuum and the environmental conditions were used at the time of the data reduction to correct the wavenumber scale. We do not know how the wavenumber scale was calibrated for spectra without environmental conditions. Where records exist 20 C and 600 mm were the temperature and

pressure inputs. If wavelength is desired this is generally expressed in air at STP. There are several different conversions, the most frequently cited is Edlén (1953) but this may lack the accuracy required. Allende Prieto (2011) summarizes recent information on wavenumber to wavelength conversion.

In addition to the original metadata we have added, the J2000 coordinates noted above, photometric magnitudes in UBVRIJHK wavebands, spectral types, and object classifications from SIMBAD to facilitate searches by color, spectral type, and object class.

4. SpArc Portal Design

4.1. SpArc Architecture

The design of the SpArc web portal followed principles laid out by Gopu et al. (2014) and Young et al. (2015, 2016) for Scalable Compute Archive (SCA) systems developed through the Trident project at Indiana University. The archive employs a modern, intuitive web interface for searching, identifying, and viewing the spectra without the user directly accessing the data. PHP/Zend, Twitter/Bootstrap, AngularJS, and the HighCharts JavaScript library are used to produce the web interface elements, and these are connected by a REST API to backend data registration and retrieval services written in Python. A key element in the design is the reuse of components common to multiple projects and only modifying or developing those elements that are unique to meet the requirements of SpArc. Common components include metadata registration, data retrieval, authentication and authorization, and database querying. Components that were customized for SpArc include user interface elements, metadata harvesting, and data visualization.

4.2. SpArc Search Options

Several search options enable the user to find and examine spectra of interest in the archive, as shown in Figure 5. A name resolver will obtain J2000 coordinates from SIMBAD to carry out a search by position on the sky. The search tool defaults to a two arc second cone search, but larger diameter cone and box searches can be selected. The user also has the option to search using specific B1950 or J2000 equatorial, galactic, or ecliptic coordinates in either decimal or sexagesimal format.

Alternatively, the user can enter a specific object name, spectral classification, or object class to identify all targets matching the entered criteria (for example, all stars of spectral

type K). Users who wish to identify all observations matching specific color or magnitude ranges, or observed within a specific date range, may also search on those criteria. The advanced search options allow the user to select spectra matching either any or all of the criteria (the default is to match all criteria). Options to include low resolution scans and scans with uncertain dates can also be selected. A batch search option allows users to find all observations matching a list of object names or coordinates. The final search results are displayed in a table. Table column headings can be customized to assist individual users to identify the spectra they need, and the table columns can be resorted as needed.

Once a list of spectra matching the desired criteria is found, users can review the individual spectra and associated metadata. A table of all other spectra obtained on that date is also provided to assist with identifying calibration spectra for telluric line division. Users can download an individual spectrum or all of the spectra obtained on a given date, in FITS format. Forward and backward FTS scans are stored as FITS extensions.

4.3. The SpArc Spectrum Viewer

The quick-look spectrum viewer provided with the archive and shown in Figure 6 enables users to view both the full range of the spectrum and also to zoom in to display portions of the spectrum at full resolution. The spectrum viewer makes use of the HighCharts JavaScript library to display the spectral data, which was extracted from the individual FITS files during data registration and saved as a JSON-formatted file. The user can zoom into a narrow region of the spectrum by dragging the left and right limits to delineate the region of interest. The region can be shifted left or right using the slider provided. Display of either the forward or backward scan can be toggled, with both scans being overlaid by default. The wavenumber and intensity values appearing in the viewer are determined using a binned average of spectrum points to fit within the browser window. As the spectral region is narrowed, fewer and fewer points are included in each binned region until all data points are displayed with the full resolution of the spectrum.

5. Contents of the Archive

The archive includes nearly 900 individual (non-solar system) targets including 780 individual stars, most with multiple observations. The stars are distributed in spectral type as summarized in Table 2. Observations of the Galactic center, variety of protostars and Galactic star-forming regions, and several galaxies are also available. In addition to these

targets, the dataset includes multiple observations of Mercury, Venus, Mars, Jupiter, Saturn, Uranus, Neptune, Comet IRAS, Titan, Io, and the Moon.

Because calibration observations are needed to remove telluric lines, many observations of Vega, Sirius, and other hot stars were obtained and are included in the archive. These include 383 spectra of Vega and 200 spectra of Sirius. Mercury and the Moon were observed in the thermal IR as telluric standards. The telluric features present in these infrared spectra provide information about the Earth’s atmospheric composition and physical condition during the period 1975-1995. These data are available for analysis to monitor changes in the atmosphere over time, and to establish a baseline against which future changes can be compared. However, users interested in research of this type may find the broader band width, higher resolution, higher signal-to-noise data from the McMath-Pierce FTS more applicable.

5.1. Sample Use Cases

The FTS Spectral Archive will support research on a variety of science goals relating to the roles of mass loss, rotation, and magnetic fields in the lives of stars, especially at the later stages of stellar evolution. The spectra will be of continuing utility in calibrating and interpreting SDSS-III APOGEE spectra collected by the Sloan Consortium (Smith 2013) and other infrared spectroscopic surveys. Furthermore, advances in stellar accretion and mass models since the 1980s will lead to more rigorous analyses of the many young stellar objects and proto-planetary nebula included in the archive, helping to move those fields forward. Studies of stellar magnetic fields will also benefit from access to the FTS spectra, since Zeeman splitting increases with wavelength, so that fields are more detectable with infrared spectra than with optical spectra. In addition to the many features of CN, CH, CO, OH, NH, HF, HCl, SiO and their isotopes, spectral features of interest in the 1-5 μm regime include the Paschen, Brackett, and Pfund series of hydrogen, many C I, Mg I, Si I lines and features of Al, P, S, and K. S-process elements are represented by Sr. Finally, the spectral coverage for some targets includes the He I 1.083 μm feature, useful for diagnosing chromospheric activity.

Three sample use cases are described below.

1. A user wishes to identify all spectra of the RV Tauri star R Sct in the K band. SpArc returns a list of 20 observations of R Sct obtained between November, 1982, and March 1983. Two of the spectra were observed at longer wavelengths (around 3000 cm^{-1}) and one at a shorter wavelength (6000 cm^{-1}). Eighteen observations were observed in the 4000-4300 cm^{-1} region. Close examination of the spectra identifies several that cover the specific spectral

region of interest. After viewing and downloading each, the user also identifies spectra of Vega and other calibration observations taken on the same date, and downloads those as well. Each observation includes a forward and backward scan, which the observer averages to get a combined spectrum. The user removes telluric lines from each R Set spectrum to produce the final spectra needed for analysis.

2. A user wishes to model high spectral resolution, high signal-to-noise line profiles of the He I 10830 Å feature in early type stars to constrain better the atomic parameters of the He I atom (Pryzbilla 2005). The user identifies numerous spectra of early type stars in the archive, sorts the spectra by wavenumber, and downloads all of the spectra that include the 10830 Å spectral region. Multiple observations available for some stars are examined to look for variability in the feature, and combined to produce higher S/N ratio spectra than possible with individual observations.

3. For late K and M giants where the peak thermal emission falls in the infrared, temperatures are best determined in the H and K bands. The broad spectral coverage of the FTS in the H and K bands gives access to lines in both the first and second overtone vibration-rotation bands of the CO molecule, providing a sensitive discrimination of temperature. Temperatures derived using CO features in late type giants can be compared directly with temperatures determined from occultation and interferometric measurements or the infrared flux method to fine-tune the temperature scale for such stars, and establish the use of CO features to determine the temperatures for fainter, more distant late-type giants observed with modern infrared spectrographs. A user can access the necessary H and K band spectra using the archive.

6. Summary

We have described the Indiana University SpArc portal for spectra obtained with the FTS on the Mayall 4-m telescope at Kitt Peak during the years 1975-1995. Both the instrument itself and data reduction procedures have been documented, and we have described the structure, contents, and use of the archive. Three possible use cases covering diverse science topics have been presented. The archive is freely available for scientific use, and can be accessed at <https://sparc.sca.iu.edu>. Users should acknowledge NOAO (see our acknowledgments for an example) and the Indiana University SpArc portal.

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for his/her prompt and enthusiastic review of our manuscript. The data discussed in this article were obtained with FTSS at the Mayall 4-meter Telescope at Kitt Peak National Observatory (KPNO). KPNO is a division of the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation. This research has made use of the NASA Astrophysics Data System Bibliographic Services, as well as the SIMBAD database, operated at CDS, Strasbourg, France. C.A.P. acknowledges the generosity of the Kirkwood Research Fund at Indiana University.

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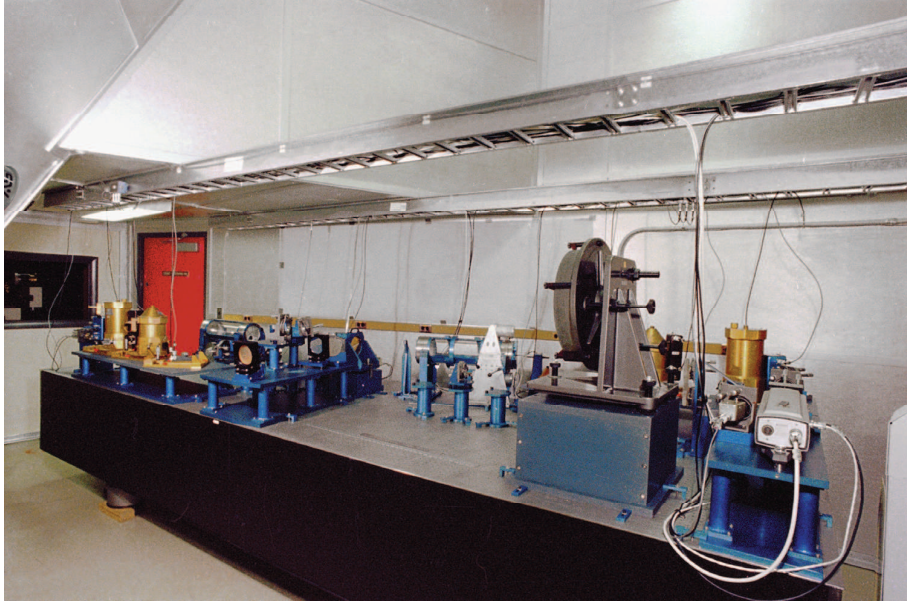


Fig. 1.— Photograph of the Mayall Fourier Transform Spectrometer in the east coudé room. The number 5 coudé mirror was through the window at the left. The number 5 coudé mirror tracked the $f/160$ beam onto the large mirror on the right. The reference laser can be seen to the right of large mirror. Image Credit: NOAO/AURA/NSF

Table 1. Questionable Spectrum Identifications

Date of Obs.	Name Logged by Observer	Object at Tel. Coords
10 May 1979	MU U MA	alf Uma
24 Sept. 1980	ZETA TAU 1	eps Tau
23 Dec. 1980	V VUL	T Vul
21 Feb. 1981	ETA=62 CYG	Xi Cyg
13 Feb. 1984	BETA TAU	eps Aur
10 Feb. 1985	ALPHA BOO	...
25 Jan. 1986	MrK 321	Mrk 231
13 July 1992	ST HER	OP Her

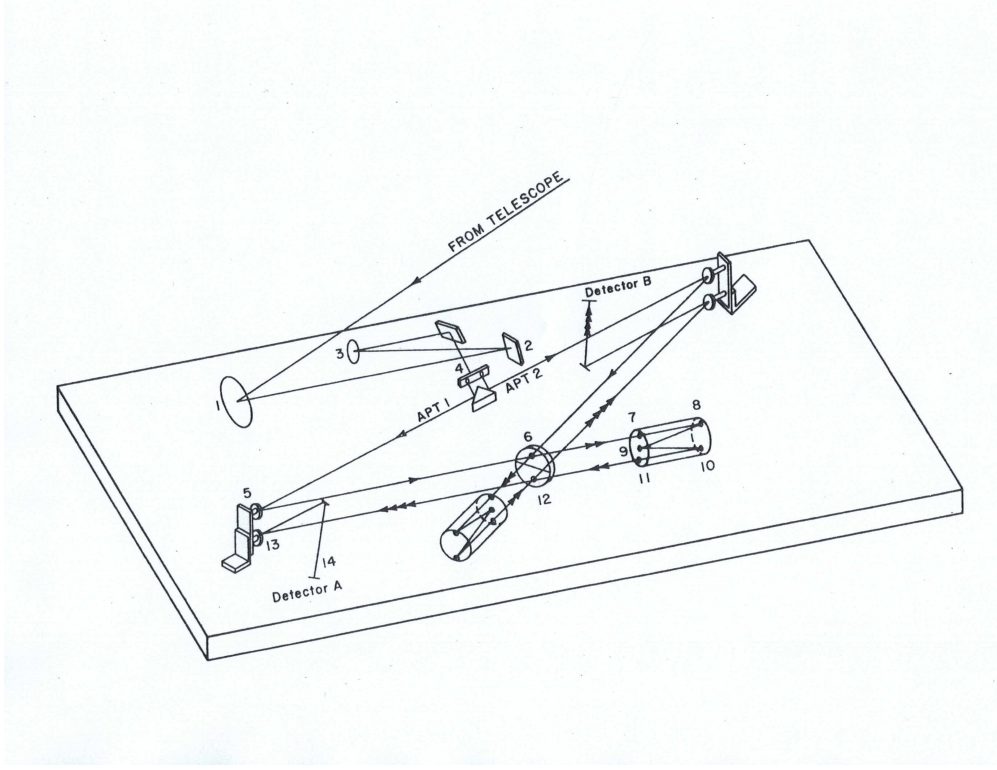


Fig. 2.— Optical layout of the facility FTS at the Mayall 4-m telescope at Kitt Peak National Observatory. Optical components are discussed in Section 2.1. This figure is Figure 2 from Hall et al. (1979, Proc. SPIE, 172, 121) and is used with permission of D.N.B. Hall and the SPIE.

Table 2. Spectral Types Represented in the Archive

Spectral Type	Number of Stars	Spectral Type	Number of Stars
O	11	K	135
WR	7	M	257
B	65	R	7
A	65	N	8
F	47	S	30
G	88	C	60



Fig. 3.— A beamsplitter from the facility FTS. The substrate for this beamsplitter, designed for use at $4.6\ \mu\text{m}$, is a 23 mm thick CaF_2 plane-parallel plate. Note the split coating design and the four tabs for the reference laser. The opposite sides of the blank from the visible coatings were anti-reflection coated. Image Credit: NOAO/AURA/NSF

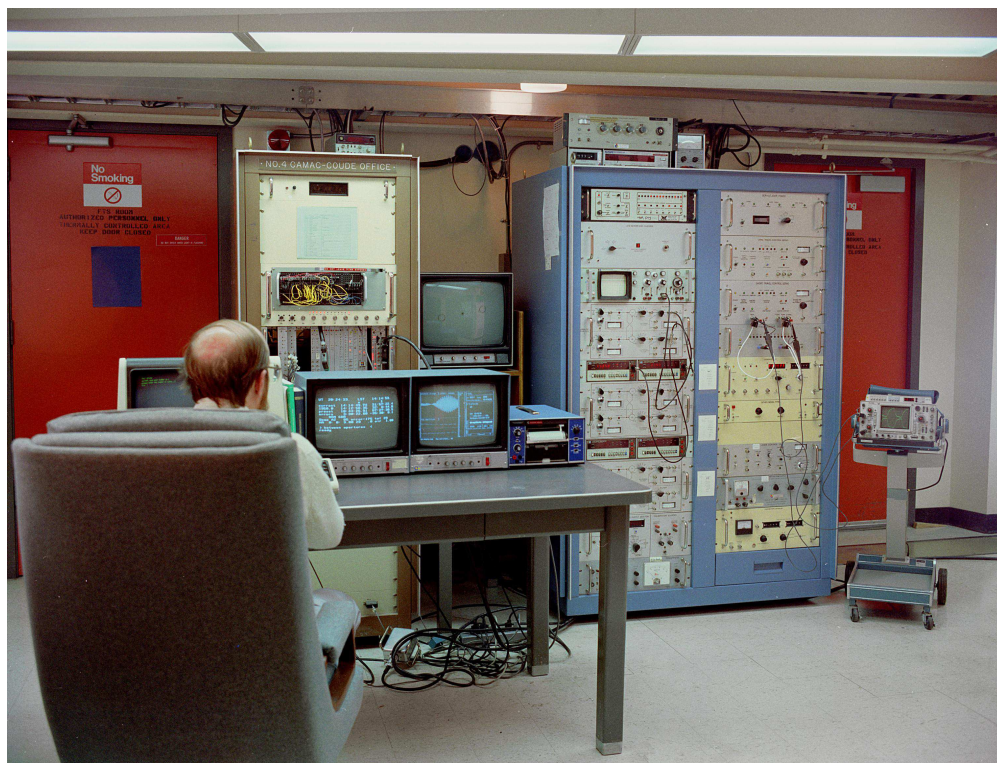


Fig. 4.— Photograph of the FTS observing room during an observing session. KHH is the observer. The right hand electronics bay held the servo and laser electronics. The middle bay held the analog electrical filters for the interferograms and the A/D converter. The left hand bay was used for computer communication. The central fringe of a K band interferogram appears on the monitor. Image Credit: NOAO/AURA/NSF

The image shows a web-based search interface for the Mayall FTS Spectral Archive. The interface is organized into several sections for filtering search results:

- Position:** Includes a search box with a dropdown menu (currently showing 'Cone'), a checkbox for 'Box', and a 'Resolve' button. Below this are dropdowns for 'Equatorial', 'J2000', and 'Sidereal'. There are also input fields for 'RA' (with a unit of α) and 'DEC' (with a unit of δ), and a 'Radius' field with a unit of 'arcsec'.
- Classification:** Includes input fields for 'Object Name', 'Object Class', and 'Spectral Type'. There is also a 'Wavenumber' section with a 'Peak (cm⁻¹)' input field and a unit dropdown.
- Date:** Includes two date input fields.
- Magnitude:** Includes a green '+ Add Limit' button.
- Color:** Includes a green '+ Add Limit' button.

At the bottom right, there is a 'Show Advanced' link and two buttons: 'Search' (with a magnifying glass icon) and 'Clear' (with a trash can icon). The footer of the page states: 'Designed and built by Indiana University' with the university logo, and 'Code licensed under MIT, documentation under CC BY 3.0 by The Trustees of Indiana University'.

Fig. 5.— The SpArc search tool.

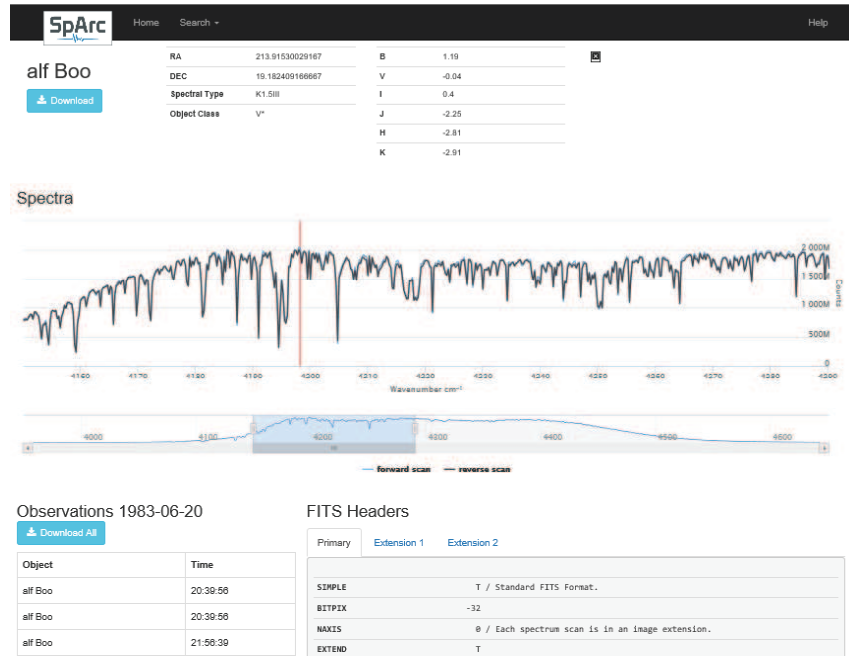


Fig. 6.— The SpArc spectrum display tool.